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In-situ measurements from mobile platforms: An emerging approach to address the old challenges associated with forest inventories

Xinlian Liang[a,b], Antero Kukko[a,b,c], Juha Hyyppä[a,b], Matti Lehtomäki[a,b], Jiri Pyörälä[a,b], Xiaowei Yu[a,b], Harri Kaartinen[a], Anttoni Jaakkola[a,b], Yunsheng Wang[a,b,*]

[a] Department of Remote Sensing and Photogrammetry, Finnish Geospatial Research Institute, 02431 Masala, Finland
[b] Centre of Excellence in Laser Scanning Research, Academy of Finland, 00531 Helsinki, Finland
[c] Department of Real Estate, Planning and Geoinformatics, Aalto University, 02150 Espoo, Finland

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ABSTRACT

Accurate assessments of forest resources rely on ground truth data that are collected via in-situ measurements, which are fundamental for all other statistical- and/or remote-sensing-based deductions on quantified forest attributes. The major bottleneck of the current in-situ observation system is that the data collection is time consuming, and, thus, limited in extent, which potentially biases any further inferences made. Consequently, conventional field-data-collection approaches can hardly keep pace with the coverage, scale and frequency required for contemporary and future forest inventories. In-situ measurements from mobile platforms seem to be a promising technique to solve this problem and are estimated at least 10 times faster than static techniques (e.g., terrestrial laser scanning, TLS) at the plot level. However, the mobile platforms are still at the very early stages of development, and it is unclear which three-dimensional (3D) forest measurements the mobile systems can provide and at what accuracy. This study presents a quantitative evaluation of the performance of mobile platforms in a variety of forest conditions and through a comparison with state-of-the-art static in-situ observations. Two mobile platforms were used to collect field data, where the same laser-scanning system was both mounted on top of a vehicle and wore by an operator. The static in-situ observation from TLS is used as a baseline for the evaluation. All point clouds involved were processed through the same processing chain and compared to conventional manual measurement. The evaluation results indicate that the mobile platforms can assess homogeneous forests as well as static observations, but they cannot yet assess heterogeneous forest as required by practical applications. The major challenge is twofold: mobile-data coverage and accuracy. Future research should focus on the robust registration techniques between strips, especially in complex forest conditions, since errors of data registration results in significant impacts on tree attributes estimation accuracy. In cases that the spatial inconstancy cannot be eliminated, attributes estimation in single strips, i.e., the multi-single-scan approach, is an alternative. Meanwhile, operator training deserves attention since the data quality from mobile platforms is partly determined by the operators' selection of trajectory in the field.

1. Introduction

Forests is an essential provider of ecosystem services, such as carbon sequestration, which attracts increasing attention from policy makers and researchers specifically in the context of climate change, bioenergy and carbon sinks. To assess the amount and distribution of forest resources, forest information is gathered at various scales and at different user levels, e.g., from worldwide political decision making to operational forest management and from countrywide inventories to stand-level measurements. Accurate assessments of forest resources rely on the sampling of ground truth that is collected with in-situ measurements, which are fundamental for all statistical- and/or remote sensing-based deductions on quantified attributes of forests.

In-situ forest measurements are usually conducted in established sample plots, e.g., typically a small forest area with a radius approximately 10 m. To systematically represent the gradients of forest compositions and structures over a large area, the sample plots are usually widespread spatially throughout forested areas. Measuring trees precisely in sample plots, as well as re-measuring them with sufficient temporal resolutions, is crucial for correctly understanding the forest ecosystem, its dynamics and its functional traits. However, precise measurement is not straightforward since forests, especially natural

* Corresponding author at: Department of Remote Sensing and Photogrammetry, Finnish Geospatial Research Institute, 02431 Masala, Finland.
E-mail address: yunsheng.wang@nls.fi (Y. Wang).

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forests, are characterized by high structural complexity and, consequently, in-situ measurements are difficult to implement. The number of sample plots that can be measured in practice are limited to a rather small number, which therefore accounts for less environmental heterogeneity and potentially biases any inferences made since errors affect the estimates calculated for a large area.

The lack of efficient inventory tools is an old and well-known challenge related to forest in-situ measurements. Unfortunately, it remains for its presence. Consequently, the forest structure beyond the sample plots and the tree structure at the individual-tree level are practically immeasurable and are therefore conventionally represented by the means and totals over the area of interest, despite the fact that forest structures vary in three-dimensional (3D) space and play an essential role in forest biophysical activities. For example, the stem curve (the function of stem diameters with respect to the height of the stem representing the stem shape) is the determining factor to estimate tree growth, stem quality and volume, but is rarely measured in-situ because it is too costly to acquire using conventional tools. Instead, it is estimated from regional or national allometric models, which are typically developed elsewhere with different climatic, geographic and silvicultural conditions and, therefore, not necessarily representative of individual trees. Even in a case when the stem curve is measured, its remeasurement is not guaranteed or it lacks the temporal resolution required for many applications. Another example is tree position, which is directly linked to the 3D forest structure and is the key parameter to match observations from different sources and from different points in time. However, measuring the tree position with centimeter-level accuracy is, in practice, extremely time-consuming due to the difficulty of collecting those measurements and the degradation of the Global Navigation Satellite System (GNSS) signals.

Lately, technologies such as the point clouds from terrestrial laser scanning (TLS) and images have presented feasible options for applying automated measurements to in-situ forest attributes, which have the capacity to provide 3D forest structure data accurately and automatically, e.g., the stem curves, and to improve the efficiency of field sampling. A main challenge lies in the speed of data acquisition. For example, a 1000 m^2 forest plot requires 20–60 min to measure using a stationary TLS.

The current question is whether in-situ 3D digitizing technologies can be promoted to the next level, in which tree- and plot-level attributes over large areas can be retrieved rapidly, accurately and cost-efficiently. Integrating 3D point cloud collection technologies with mobile platforms can provide a solution to the problem. A mobile system may consist of platforms with high mobility, e.g., car, all-terrain-vehicle, and human operator; one or several instrument, e.g., laser scanner(s) and/or camera(s); and positioning and orientation sensors, e.g., GNSS and/or inertial measurement units (IMU). The main advantages of such a system are its high mobility in various terrain conditions and its high flexibility for rapid data collection. It was shown in a previous study that the mobile system was 3 to 10 times faster than TLS and cameras (Liang et al., 2015). At this moment, mobile observations in forest environments are still in the very early stages of development. The limited studies were mainly on system demonstration in forests with simple structures, e.g., (Liang et al., 2014a, 2014b; Ryding et al., 2015; Bauwens et al., 2016; Forsman et al., 2016b; Marselis et al., 2016; Juraj et al., 2017; Oveland et al., 2017; Campos et al., 2018), but the usability of a mobile platform in varying forest stand conditions for forest in-situ observations has not been investigated. The quality of tree attribute data derived from contemporary mobile systems remains unclear.

This study evaluated the performance of mobile systems in various forest stand conditions, focusing on three critical factors, i.e., the 3D forest structure, the accuracy of the attribute estimates, including the stem tapering, volume and above-ground biomass (AGB), and the measurement efficiency. A comparison is also made between mobile systems and state-of-the-art of static observations from laser scanning. The findings in this paper are expected to provide orientations for exploring the new horizons of in-situ quantificational mapping of forests utilizing mobile platforms.

2. Materials and methods

The study in this work was based on 24 forest plots representing a variety of stand conditions with regard to species, growth stages and management activities. As references, the same plots were also measured using conventional in-situ measurements and state-of-the-art TLS. Point clouds were processed through the same processing chain and the results were evaluated using conventional measured references.

2.1. Test area

In 2014, 24 forest plots were selected by foresters in a southern boreal forest in Evo, Finland (61.19°N, 25.11°E) to be a test bed for various in-situ measurement techniques. The selected forest plots represent a variety of stand conditions with regard to species, growth stages and management activities, which were classified into three complexity categories from a forest inventory point of view, i.e., “easy”, “medium” and “difficult”. The complexity categories were defined based on stem visibility (the level of possible occlusion effects) at the ground level, the spatial stem density and the diameter at breast height (DBH) distribution of the sample plots. The category “easy” represents clear visibility with minimal understory vegetation and low stem density (~600 trees/ha); “medium” represents sample plots with moderate stem densities (~1000 trees/ha) and sparse understory vegetation; and the “difficult” category represents plots with high stem densities (~2000 trees/ha) and dense understory vegetation. Fig. 1 shows the plot-specific statistics of the mean DBH and the mean tree height to represent the variation in tree size for the sample plots.

Each plot has a fixed size of 32-by-32 m. The main tree species are Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (H. Karst.) L.) and Silver (*Betula pendula* Roth) and Downy (*Betula pubescens* Ehrh.) birches.

In this study, 23 of the 24 plots were measured from mobile platforms; data collection in one plot was unsuccessful because the field crew located the plot incorrectly during the operation. Therefore, the test results refer to 23 test plots and are also comparable to results from other tests based on the same test bed where all 24 plots are included.

2.2. Reference collection using TLS and conventional in-situ measurements

To accurately evaluate the performance of the mobile mapping systems, the same test plots were recorded with stationary TLS. The measurements were made in 2014 using Leica HDS6100 (Leica Geosystems AG, Heerbrugg, Switzerland) and the multi-scan approach. Five scans were made in each test plot: one scan at the plot center and four scans at the four quadrant directions, which represents the most accurate non-contact measurement in the field. Artificial spheres were set up as reference targets throughout the plot for the data registration. The registration accuracy is at a 2 mm level. The point spacing is 15.7 mm at 25 m from the scanning location in both horizontal and vertical directions. The forest was scanned as is, i.e., without any pre-scan preparation, such as removing lower tree branches or clearing undergrowth.

Conventional forest in-situ measurements were carried out in 2014. For each sample plot, a map of trees was measured by combining manual measurements from the multi-scan TLS data and the measurements taken in the field. Tree positions were preliminarily mapped from 3D TLS points and verified later in situ. All trees having a DBH larger than 5 cm were included in the plot tree maps.

Tree attributes, i.e., the tree height and the DBH, were measured for each tree using conventional field measurement methods, while the stem curves were manually digitized through multi-scan TLS point